

Effect of OH depletion on measurements of the mass-to-flux ratio in molecular cloud cores

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ABSTRACT

The ratio of mass and magnetic flux determines the relative importance of magnetic and gravitational forces in the evolution of molecular clouds and their cores. Its measurement is thus central in discriminating between different theories of core formation and evolution. Here we discuss the effect of chemical depletion on measurements of the mass-to-flux ratio using the same molecule (OH) both for Zeeman measurements of the magnetic field and the determination of the mass of the region. The uncertainties entering through the OH abundance in determining separately the magnetic field and the mass of a region have been recognized in the literature. It has been proposed however that, when comparing two regions of the same cloud, the abundance will in both cases be the same. We show that this assumption is invalid. We demonstrate that when comparing regions with different densities, the effect of OH depletion in measuring changes of the mass-to-flux ratio between different parts of the same cloud can even reverse the direction of the underlying trends (for example, the mass-to-flux ratio may appear to *decrease* as we move to higher density regions). The systematic errors enter primarily through the inadequate estimation of the mass of the region.

Key words: ISM: clouds – ISM: magnetic fields – ISM: abundances – ISM: molecules – MHD – stars: formation

1 INTRODUCTION

Identifying the mechanism that regulates the star formation process and keeps the star formation efficiency low is at the heart of current theoretical and observational efforts. Magnetic fields and turbulence are the two main contestants for the role of the agent that (a) supports molecular clouds against gravity so that they are not globally collapsing and (b) mediates cloud fragmentation into cores that will later go on to form protostars. Despite several decades of theoretical study and observations, which of the two mechanisms is dominant in molecular clouds is still a matter of heated debate. The reason is that the two appear to be in rough equipartition in cold molecular clouds (Heiles & Troland 2005), and observational degeneracies and uncertainties have thus far thwarted efforts to declare a clear winner.

The ratio between mass and magnetic flux (the *mass-to-flux ratio*, M/Φ_B) is a quantity of central importance in moving this debate forward, for two reasons. First, it quanti-

fies the effectiveness of the magnetic field alone in supporting a cloud against gravity: if the mass-to-flux ratio exceeds a critical value

$$\left(\frac{M}{\Phi_B}\right)_{\text{crit}} = \left(\frac{1}{63G}\right)^{1/2}, \quad (1)$$

(Mouschovias & Spitzer 1976), then the magnetic field cannot support the region in question against its self-gravity and, in absence of any other means of support, the region will collapse dynamically. Such a region is called *magnetically supercritical*. If on the other hand the mass-to-flux ratio is smaller than the critical value, then magnetic forces alone can support the region against its self-gravity. Such a region is called *magnetically subcritical*.

If molecular clouds are magnetically subcritical as a whole, then in order for gravitational collapse to take place, magnetically supercritical fragments have to first form within them. This is achieved through the process of ambipolar diffusion: because of the imperfect coupling between magnetic fields and the neutral gas in weakly ionized molecular clouds, neutral molecules can move diffusively through ions and magnetic field lines and increase the mass-to-flux ratio around centers of gravity. In this way, supercritical

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cores can form within subcritical clouds (e.g., Fiedler & Mouschovias 1993.) In order for a molecular cloud core to be observable as a distinct fragment, it typically is already supercritical (e.g. Tassis & Mouschovias 2004.)

This mechanism of core formation leaves a characteristic imprint on the relative mass-to-flux ratio between supercritical core and subcritical envelope: the core always has a higher mass-to-flux ratio than its parent cloud envelope. Crutcher et al. (2009) took advantage of this property to design a test of ambipolar diffusion as a core formation mechanism. They attempted to measure, through OH Zeeman splitting, the magnetic field of cloud envelopes in locations around four cores with previously measured magnetic fields. They additionally used the integrated intensity of OH to estimate the mass in cores and envelopes. Their quantity of interest was the ratio R' between the mass-to-flux ratio in the core over the mass-to-flux ratio in a larger area, enclosing both core and envelope, which ambipolar-diffusion-driven fragmentation predicts should be higher than or equal to one.

Crutcher et al. (2009) argued that, because the quantity they are trying to determine is a ratio between the same quantities in different regions of a single cloud, unknown parameters, such as the orientation of the magnetic field with respect to the line of sight and the OH abundance, drop out. The uniform orientation assumption, as well as the particulars of the Crutcher et al. (2009) implementation (selection of locations of Zeeman observations in the cloud envelopes, statistical treatment of upper limits) have been criticized in the literature (Mouschovias & Tassis 2009, 2010.) Chemistry can also affect such an experiment because the OH abundance and the magnetic field are convolved in a Zeeman measurement (Tassis et al. 2012b). However, we show here that the biggest source of systematic errors in such experiments is the effect of chemistry on the mass estimate.

Briefly stated, the chemical process of OH depletion onto grains invalidates the assumption of a common OH abundance throughout the cloud. Depletion makes the OH abundance lower in higher density regions, leading to an underestimate of their total mass and consequently an underestimate of their mass-to-flux ratio. As a result, the mass-to-flux ratio of a supercritical fragment can appear *lower* than that of the subcritical envelope, *even if all other assumptions hold, and all other parameters and analyses of the experiment are exactly correct.*

Here we quantify this effect, using chemodynamical MHD models that follow concurrently the evolution of density, magnetic field, and chemical abundance in a forming and evolving molecular cloud core. We trace the origin of the effect in the radial dependence of mass and magnetic field in ambipolar-diffusion-produced cores within molecular clouds of various initial parameters; and we suggest a straightforward way to overcome this systematic error: use of *dust continuum emission* rather than OH intensity to measure the masses that enter into mass-to-flux ratio estimates.

This paper is organized as follows. In §2 we briefly review the suite of chemodynamical models used in this work. We use these models in §3 to construct simulated observations which demonstrate the effect of chemistry on estimates of mass and the mass-to-flux ratio in simulated cores. Finally, we summarize and discuss our conclusions in §4.

2 CHEMODYNAMICAL MODELS

For the simulated observations presented here, we use the suite of 1.5D magnetic chemodynamical models described in detail in Tassis et al. (2012a) and used in Tassis et al (2012b) to study the effect of OH depletion on the measurement of the magnetic field. We briefly review their properties below.

We use results from 14 models of evolving prestellar cores that couple nonequilibrium chemistry with nonideal magnetohydrodynamics. The parameters that are varied are the initial value of the mass-to-flux ratio; the initial elemental C/O ratio; the cosmic-ray ionization rate; and the cloud temperature.

Our “reference” model has a mass-to-flux ratio equal to the critical value for collapse, a temperature of 10 K, a C/O ratio of 0.4, and a cosmic ray ionization rate of $\zeta = 1.3 \times 10^{-17} \text{ s}^{-1}$. We examine two additional values of the initial mass-to-flux ratio: 1.3 times the critical value (a faster-evolving, magnetically supercritical model), and 0.7 of the critical value (a slower, magnetically subcritical model). For each of these three dynamical models, the carbon-to-oxygen ratio is varied from its “reference” value by keeping the abundance of C constant and changing that of O. The other value of C/O ratio examined is 1. In addition, to test the effect of the temperature, we have varied each of the three basic dynamical models by changing T by a factor of ~ 1.5 from its reference value of 10 K and examined models with $T = 7 \text{ K}$ and $T = 15 \text{ K}$. Finally, to test the effect of the cosmic ray ionization rate, we have studied two additional models, which have a “reference” value for the temperature, C/O ratio, and mass-to-flux ratio, but for which ζ is varied by a factor of four above ($\zeta = 5.2 \times 10^{-17} \text{ s}^{-1}$) and below ($\zeta = 3.3 \times 10^{-18} \text{ s}^{-1}$) its “reference” value (covering the range of observational estimates (e.g. McCall et al. 2003; Hezareh et al. 2008)).

3 SIMULATED OBSERVATIONS

We first use the models discussed in §2 to construct an idealized experiment similar to the one proposed by Crutcher et al. (2009). Because of the presence of an ordered magnetic field, each forming core preferentially collapses along field lines (where there is no magnetic support), thus assuming a disk shape. We assume that the disk is observed face-on. We define a “dense core” in each model to be a disk extending out to the radius where the number density of H_2 is equal to 10^4 cm^{-3} , and a “core+envelope” region to be a disk extending out to where $n_{H_2} = 10^3 \text{ cm}^{-3}$. For each model, and at various stages of evolution, we measure the mass-to-flux ratios of “dense core”, M/Φ_4 , and “core+envelope”, M/Φ_3 , using the exact quantities for mass and magnetic flux recorded in our simulations. We then plot their ratio, $R' = (M/\Phi_4)/(M/\Phi_3)$ as a function of evolutionary stage. The latter is quantified by the value of the central density in the core at every time instant. These results are shown in Fig. 1. The ratio between mass-to-flux ratios is slightly above unity for all models, but no higher than 2. As expected (e.g. Fiedler & Mouschovias 1993 ?), there is essentially no evolution of the mass-to-flux ratio of the cores during these stages of collapse: the envelope is magnetically supported and neither its mass nor its magnetic flux evolve in time;

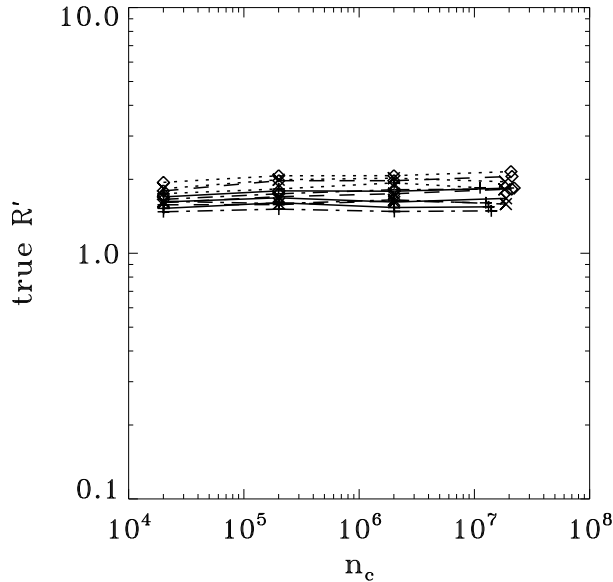


Figure 1. Actual value of $R' = (M/\Phi_4)/M/\Phi_3$ as a function of central density of the core, for the various models used in this work. Models correspond to symbols and line types as follows: Diamonds: magnetically subcritical; X: magnetically critical; crosses: magnetically supercritical; solid lines: reference C/O, T, ζ ; dotted lines: C/O=1; dashed lines: low T; dot-dashed: high T; thick line: high ζ ; thin line: low ζ .

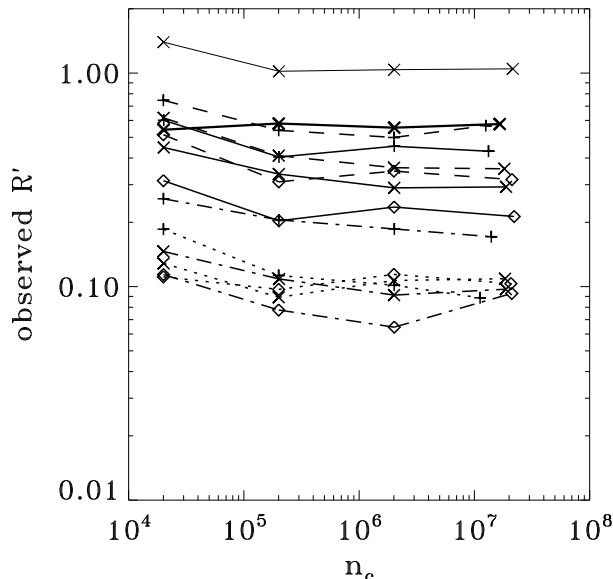


Figure 2. Simulated observations of $R' = (M/\Phi_4)/M/\Phi_3$ as a function of central density of the core, for the various models used in this work. Symbols and lines as in Fig. 1.

the mass-to-flux ratio of the core is also steady after the onset of dynamical collapse, and before the “resurrection” of ambipolar diffusion, seen at densities around 10^{10} cm^{-3} (Desch & Mouschovias 2001; Tassis & Mouschovias 2007.)

Next, we use our simulations to reproduce what a “realistic” experiment would look like: we calculate the mass and magnetic flux that would be estimated for the “dense

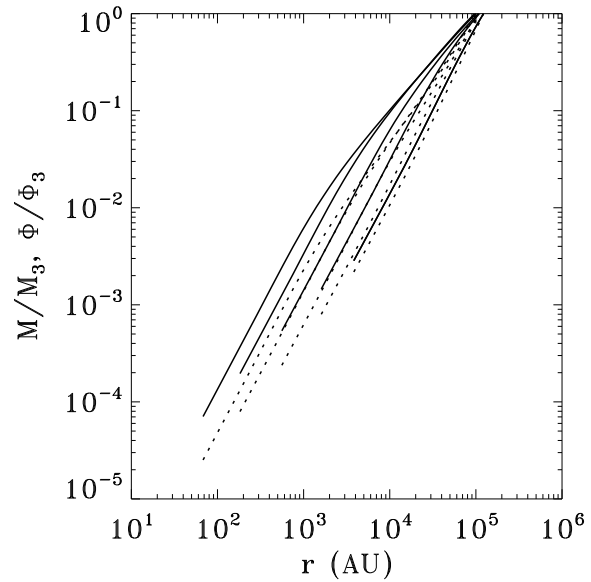


Figure 3. Scaling of the total (cumulative) mass (solid lines) and magnetic flux (dotted lines) with radius, for a region of the cloud with an outer boundary at 10^3 cm^{-3} . Each curve corresponds to a different evolutionary stage.

core” and “core+envelope” regions using Zeeman observations and observations of the OH line intensity respectively. To do this, we assume that the magnetic field traced by Zeeman splitting of the OH line is the OH-mass-weighted magnetic field in the region under consideration. Since our models follow both the OH abundance and the evolution of the magnetic field, this quantity is easily calculated. In addition, we assume that the cloud is optically thin in OH line emission, and therefore the OH intensity is proportional to the OH column density. The ratio of masses between core and core+envelope (which enters the estimation of R') is thus simply the ratio between OH masses between the two regions, a quantity that is directly followed in each model.

OH depletion affects the measurement of both the magnetic field and the mass *in the same direction*, so it is not *a priori* obvious whether R' would end up underestimated or overestimated. The mean magnetic field is underestimated, as discussed in Tassis et al. (2012), because OH is more depleted in the higher density regions, where the magnetic field is also high. The total mass in the highest density regions also appears lower in OH intensity, because the OH abundance drops as the density increases.

Fig. 2 shows the ratio R' as measured in the fashion discussed above, plotted against the central number density (a proxy for the evolutionary age), for different models. In all models R' is underestimated compared to its “real” value. In all models but one, its “observed” value is lower than one, and, depending on the model, it can appear to be lower than 0.1. Ironically, the more subcritical an envelope is, the more R' deviates from its “real” value: the reason is that more subcritical models evolve more slowly and the effect of depletion is more severe.

The reason why the net effect of depletion has the sign discussed above can be traced back to the cumulative radial profiles of the total mass and total flux in the evolving

cloud. We plot these profiles in Fig. 3. The total mass (solid lines) and magnetic flux (dotted lines) are normalized to unity at a radius where the number density is 10^3 cm^{-3} . As expected for a disk-like structure, the scaling of mass and flux with radius have the same slope in the inner parts of the disk. However, the overall normalization of the scaling evolves differently in time. Because of OH depletion, it is the outermost regions that dominate the “observed” values of both mass and flux. Because of the different relative distributions of total mass and flux with radius, the “observed” mass is more severely affected than the “observed” flux, and the mass-to-flux ratio appears underestimated, more so for higher-density regions. As a result, measured values of the ratio R' tend to be lower than the true ones obtained using OH to estimate the core and envelope mass.

4 SUMMARY AND DISCUSSION

We have used a suite of chemodynamical simulations to demonstrate the effect of OH depletion on observational estimates of the mass-to-flux ratios in molecular cloud cores and envelopes, when OH intensity is used as means to estimate the mass associated with the observed region.

We have shown that, whereas OH depletion leads to the underestimation of both mass and flux in the densest regions, the effect on the mass is more severe, leading to an overall *underestimate* of the mass-to-flux ratio. The effect is more significant in the denser regions, where depletion is more severe. As a result, the mass-to-flux ratio can appear to *decrease* as we move from a subcritical cloud’s envelope to its supercritical ambipolar-diffusion-formed core - despite the fact that the mass-to-flux ratio is in reality always higher in the core.

Our result is a sobering reminder that chemical effects can be the source of severe systematic errors, for all experiments setting out to measure the mass-to-flux ratio in molecular cloud cores and envelopes. The most severe effect is that of tracer depletion on the measured mass. The effect of depletion has been observationally confirmed in several prestellar cores (e.g., Caselli et al. 1999; Tafalla et al. 2002; Tafalla et al. 2004), including L1544 (one of the cores studied by Crutcher et al. 2009).

The effect of depletion in estimates of the magnetic field, on the other hand, needs to be carefully accounted for (see also Tassis et al. 2012). As a general rule-of-thumb, Zeeman observations of a region centered on a center of gravity will always preferentially probe the outermost (least dense) parts of the region, where OH (or other tracer) depletion is least severe.

Regarding experiments specifically designed to study the gradient of the mass-to-flux ratio between cores and envelopes (e.g. Crutcher et al. 2009), we point out that the effect of depletion alone is enough to make the mass-to-flux ratio in the core appear smaller than that of the envelope. Because depletion is more severe in clouds that evolve more slowly, *the decrease of the mass to flux ratio from envelope to core will be greater when the magnetic field is more dynamically important.*

Crutcher et al. (2009) have claimed that they have constrained R' to be lower than 1 in four cases of molecular cloud cores and the envelopes surrounding them. Al-

though their statistical analysis and selection of envelope locations to observe have been challenged (Mouschovias & Tassis 2009, 2010), our findings have important implications for these results, *even if taken at face-value*. Crutcher et al. (2009) used the assumption of a constant OH abundance throughout core and envelope to estimate the ratio of masses that enters into their estimation of R' , just as we have done in our simulated observations. Therefore, any values of R' that they find to be much smaller than 1 (even if one was to otherwise accept their analysis) do not imply that a core was not formed by ambipolar diffusion.

In conclusion, the assumption of a constant OH abundance, even within a small region of the same molecular cloud, is a poor assumption when there is a density gradient in the region under consideration. Nevertheless, experiments measuring the gradient of mass-to-flux ratio between core and envelope can be important tests of the predictions of ambipolar diffusion theory, and for this reason it is imperative that they are performed carefully. In the context of this work, such experiments require the accurate determination of the core mass independent from the OH lines used for Zeeman observations, preferably using dust continuum observations. We note however that the dust-to-gas ratio can itself vary with density: Ciolek & Mouschovias (1994) found that, because of the effect on ambipolar diffusion on ionized grains, the abundance of grains in the supercritical core is reduced relative to that in the envelope by a factor that is equal to that by which the envelope is initially subcritical. This effect should therefore be corrected for in such measurements.

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